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Evaluation of empirical relationships between extreme rainfall and daily maximum temperature in Australia

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ABSTRACT

Understanding the relationships between extreme daily and sub-daily rainfall events and their governing factors is important in order to analyse the properties of extreme rainfall events in a changing climate. Atmospheric temperature is one of the dominant climate variables which has a strong relationship with extreme rainfall events. In this study, a temperature-rainfall binning technique is used to evaluate the dependency of extreme rainfall on daily maximum temperature. The Clausius-Clapeyron (C-C) relation was found to describe the relationship between daily maximum temperature and a range of rainfall durations from 6 min up to 24 h for seven Australian weather stations, the stations being located in Adelaide, Brisbane, Canberra, Darwin, Melbourne, Perth and Sydney. The analysis shows that the rainfall – temperature scaling varies with location, temperature and rainfall duration. The Darwin Airport station shows a negative scaling relationship, while the other six stations show a positive relationship. To identify the trend in scaling relationship over time the same analysis is conducted using data covering 10 year periods. Results indicate that the dependency of extreme rainfall on temperature also varies with the analysis period. Further, this dependency shows an increasing trend for more extreme short duration rainfall and a decreasing trend for average long duration rainfall events at most stations. Seasonal variations of the scale changing trends were analysed by categorizing the summer and autumn seasons in one group and the winter and spring seasons in another group. Most of 99th percentile of 6 min, 1 h and 24 h rain durations at Perth, Melbourne and Sydney stations show increasing trend for both groups while Adelaide and Darwin show decreasing trend. Furthermore, majority of scaling trend of 50th percentile are decreasing for both groups.

1. Introduction

Predicting the impact of future climate change is a real challenge for hydrologists working to mitigate damage from climatic extremes. The prediction of sub-daily extreme rainfall events is vitally important in urban stormwater modelling studies which seek to recommend future drainage requirements (Herath et al., 2016). There are several approaches are available in the literature to simulate the sub-daily extreme rainfall events and most of these studies are based on the down-scaling approach of the General Climate Model (GCM) predictors (Fowler et al., 2007; Herath et al., 2016; Willems et al., 2012). However, understanding of the occurrence of high intensified short term rainfall events is very important to improve the reliability of short duration rainfall event simulations (Lenderink and Attema, 2015; Westra et al., 2014).

Evaluating the impacts of anthropogenic climate change is essential to understanding the behaviour of short duration extreme rainfall events (Allen and Ingram, 2002; Min et al., 2011). Anthropogenic Green House Gas (GHG) emissions have significantly increased since the end of 20th century (Sachindra et al., 2016) and, in fact, it has been found that it is likely that there is a relationship between climate change and GHG emissions (Crowley, 2000; Sachindra et al., 2016). According to the Intergovernmental Panel on Climate Change (IPCC) an increase in GHG emissions has led to changes in rainfall types and patterns across the world. An increase in the occurrence of extreme events, such as floods, as a result of high intensity precipitation and droughts as a result of a lack of precipitation, have been simulated using global climate models (Easterling et al., 2000; Hirabayashi et al., 2008; IPCC, 2012) for some parts of the world. Therefore, to mitigate the damage from predicted future disasters, it is important to identify the

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dependency of these extreme events on other climate variables (Kawagoe et al., 2010).

In the context of a changing climate, research studies which evaluate the relationship between atmospheric temperature and extreme rainfall have been in demand over the last decade (Panthou et al., 2014; Utsumi et al., 2011; Wasko and Sharma, 2015). The general acceptance is that increases in temperature drive high intensity precipitation events in many parts of the world (Alexander et al., 2006; Allan and Soden, 2008; Westra et al., 2013). However, this hypothesis remains uncertain and does not mean equal influence on all regions of the world (Fischer and Knutti, 2015). Also, this hypothesis is mainly based on future climate projections as governed by the Clausius–Clapeyron (C-C) relationship and average relative humidity variations throughout the world (Soden and Held, 2006). In addition to temperature, large scale motion of the atmosphere (Emori and Brown, 2005), Changing cloud characteristics during rainfall events (KE, 2011; Trenberth et al., 2003) and changes in moist-adiabatic lapse rates (O'Gorman and Schneider, 2009) are also having significant impacts on extreme rainfall events.

According to the C-C relationship, the water holding capacity of the atmosphere increases at an exponential rate with increasing temperature. Over the last decade a number of studies have been conducted to determine the C-C scaling relationship between extreme precipitation and temperature in different parts of the world, including in Australia (Hardwick Jones et al., 2010), China (Yu and Li, 2012), Europe (Haerter et al., 2010; Lenderink et al., 2011; Lenderink and Van Meijgaard, 2008), Japan (Utsumi et al., 2011), Hong Kong (Lenderink et al., 2011) and North America (Shaw et al., 2011).

Lenderink and Van Meijgaard (2008) studied the rainfall - temperature scaling phenomena using binning technique approach and this work is recognised as a pioneering in this field. They used the binning technique to determine the scale properties of hourly rainfall events by dividing rainfall into 2 °C temperature bins. The results of this study support the C-C scaling hypothesis under some deviations. Specially, scaling between extreme rainfall and temperature vary by significant amount in some occasions. As an example, higher percentile rainfall events show increased scale of up to 15% per °C as a probable impact of intense convective rainfalls (Berg et al., 2013; Loriaux et al., 2013; Molnar et al., 2015). Furthermore, previous studies show that rainfall – temperature relationship is stronger for shorter rainfall duration than long durations. Panthou et al. (2014) studied the rainfall - temperature scaling over Canada and they observed decreasing scale with increasing rain duration. Similar behaviour of rainfall - temperature scaling is identified by Wasko et al. (2015) and Hardwick Jones et al. (2010) for the Australian storms. Also, seasonal impacts on rainfall - temperature scaling is analysed by Berg et al. (2009) and Wasko and Sharma (2014) over Australia.

However, the positive rainfall temperature scaling relationship is valid only for a certain temperature range and beyond this range negative scaling of extreme rainfall events with temperature is evident. According to the study conducted by Hardwick Jones et al. (2010), they concluded that availability of moisture is increasingly important in higher temperature. Therefore, unavailability of adequate moisture amount at higher temperature leads decline trend of scale and relative humidity.

The aim of the study described here was to evaluate the variation of the rainfall - temperature scaling relationship between daily maximum temperature and extreme rainfall events over the analysis time period. Studies described in the literature do not discuss the variation in rainfall - temperature scaling relationships over long time periods as determined by analysing the data using different windows in time. Most of the studies calculated scale by considering the whole period as one slice of time, consequently these studies do not show variations in scaling relationships for both past and present conditions. Studying variations in rainfall - temperature scale trend enables researchers to project the behaviour of extreme rainfall events in the future. Therefore this study has three main goals: (i) identify the relationship between daily and sub-daily extreme precipitation and daily maximum temperature; (ii) evaluate the variation in rainfall - temperature scale for different time slices; and (iii) analyse the impact of seasonality on rainfall – temperature scale.

2. Study area and data sets

Australia is one of the driest continents in the world and rainfall pattern throughout the Australia is highly seasonal. Rain gauge stations located across five Australian states and two territories with longest record periods and least missing data were considered for this study. Therefore, Adelaide Airport, Canberra Airport, Darwin Airport, Melbourne Airport, Perth Airport, Sydney (Observatory Hill) and Brisbane Regional rain gauge stations were selected for the study. The locations of these rain gauge stations are presented in Fig. 1.

The Australian Bureau of Meteorology (BoM) is a major provider of weather and climate data in Australia. For this study, BoM rainfall data and daily maximum temperature data were collected for the chosen sites. Detailed information on the seven selected stations is included in Table 1.

3. Methodology

The 'binning' technique, developed by Lenderink and Van Meijgaard (2008) was used in this study to evaluate the empirical relationships between precipitation and temperature. For each station, the maximum rainfall depth on wet days (defined as rainfall >0.3 mm/day) for a given duration was grouped with the daily maximum temperature. Consistent results for daily mean temperature and daily maximum temperatures have been obtained by previous studies conducted by other researchers in the same area (Hardwick Jones et al., 2010). Initial observations clearly indicated that the variation in temperature is primarily driven by seasonality in most locations. Therefore this study was carried out using yearly and seasonal lumped data.

There are few limitations have been identified by Wasko and Sharma (2014) in binning technique compare to the quantile regression approach, specially these limitations and bias are associated with the approach of equal width temperature bins. Assignment of temperature bins of equal width leads to fewer pairs in upper and lower temperature bins. Furthermore, fixing bin temperature ranges may result in empty bins being ignored and the distortion of the relationship between temperature and precipitation. By considering the drawbacks associated with the use of equal width bins, temperature bins were assigned an equal number of pairs per bin (Hardwick Jones et al., 2010) and the median temperature value of each bin was used to identify the bin. The temperature range of each bin was then estimated to be approximately 2 °C, with the temperature range of the upper and lower tails slightly greater than 2 °C. Another minor source of sampling uncertainty is related to the number of pairs in periodic samples. (As an example different number of pairs in a bin for 1991–2000 period and 2001–2010 period, etc.). In generally, sampling uncertainty takes high value at the presence of small number of pairs in a bin. When consider the periodic analysis of all stations, the median of the pairs in a temperature bin was 104 for this study. For the winter – spring season, number of pairs was 51 and summer – autumn season, it was 50. Therefore, uncertainty generates through periodic sampling is minimum in this study.

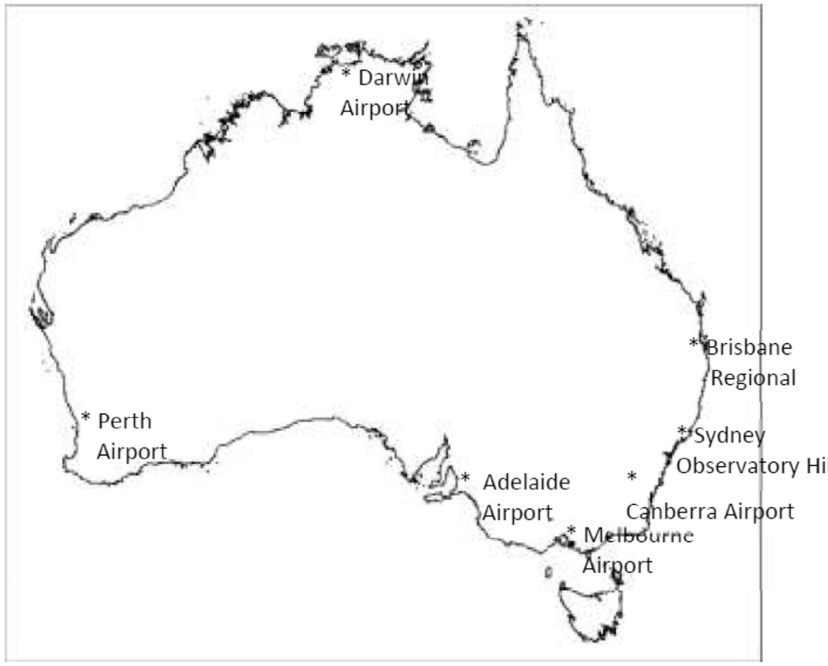


Figure 1. Location of selected rain gauges.

Table 1
Details of weather stations.

State	Weather station name	Coordinates	Data period
New South Wales	Sydney (Observatory Hill)	33.86°S, 151.21°E	1913–2010
Victoria	Melbourne Airport	37.67°S, 144.83°E	1971–2010
Western Australia	Perth Airport	31.94°S, 115.96°E	1961–2010
Northern Territory	Darwin Airport	12.42°S, 130.89°E	1954–2010
South Australia	Adelaide Airport	34.95°S, 138.52°E	1971–2010
Queensland	Brisbane Regional	27.48°S, 153.03°E	1908–1994
Australian Capital Territory	Canberra Airport	35.30°S, 149.20°E	1938–2010

To identify the C-C scaling relationship between extreme rainfalls and temperature, an exponential regression function was applied. According to the literature (Hardwick Jones et al., 2010; Utsumi et al., 2011) the relationship between precipitation (P) and temperature is described by Eq. (1).

$$P_2 = P_1(1+\alpha)^{\Delta T} \quad (1)$$

whereP_1 and P_2 are the precipitation percentiles at temperature T_1 and T_2 respectively. ΔT is the temperature difference between T_1 and T_2. α is the precipitation temperature scaling co-efficient, where $\alpha = 6.8\%\ °C^{-1}$ at 25 °C equivalent to Clausius-Clapeyron. For the rainfall - temperature scaling analysis the 99th and 50th percentiles of rainfall maxima for 6 min, 12 min, 30 min, 1 h, 2 h, 6 h, 12 h and 24 h rainfall durations were considered.

4. Results and discussion

4.1. Evaluating the rainfall-temperature scaling relationship for extreme rainfall and daily maximum temperature

Initially, by taking the total data period as one time slice, the rainfall temperature scaling relationship was estimated for extreme rainfall events and daily maximum temperature. Fig. 2 presents the distribution of the 99th and 50th percentiles of daily and sub-daily extreme precipitation with daily maximum temperature. According to Fig. 2, both the 99th and 50th percentiles of maximum rainfall events show exponential relationships with daily maximum temperature. The relationships are especially strong (more positive) for the sub-daily (6 min, 12 min, 30 min, 1 h and 2 h) rainfall durations. However, in most instances the resultant exponential scaling rate does not agree with the generally accepted C-C scale value of 6.8%C^{-1}.

Fig. 2 also shows that in general the rainfall - temperature scaling rate for the 50th percentile has a lower value than the 99th percentile scaling rate and at most stations it is very close to zero. For some stations (Adelaide, Darwin, Perth and Sydney) the scaling rate for the 50th percentile is negative for all rain durations. The most significant result apparent in Fig. 2 is that the exponential scaling relationship exists only within a certain temperature range. Specifically, the graphs show a reduction of the extreme rainfall intensities with increasing temperature between 30 °C and 35 °C (except Darwin station).

Fig. 3 was developed using Eq. (1) on the percentiles presented in Fig. 2, to present the scaling trend. Fig. 3 illustrates the variation of rainfall -temperature scaling based on station, percentile and rain duration. Fig. 3(a) describes the variation in scaling of the 99th percentile of the daily and sub-daily maximum rainfall durations (6 min to 24 h), while Fig. 3(b) describes the variation in scaling of the 50th percentile of the daily and sub-daily maximum rainfall durations (6 min to 24 h). Further, these both figures show approximately similar variation of rainfall –temperature scaling for all stations except Darwin Airport. It is also evident that with the exception of Darwin Airport, the rainfall - temperature scale

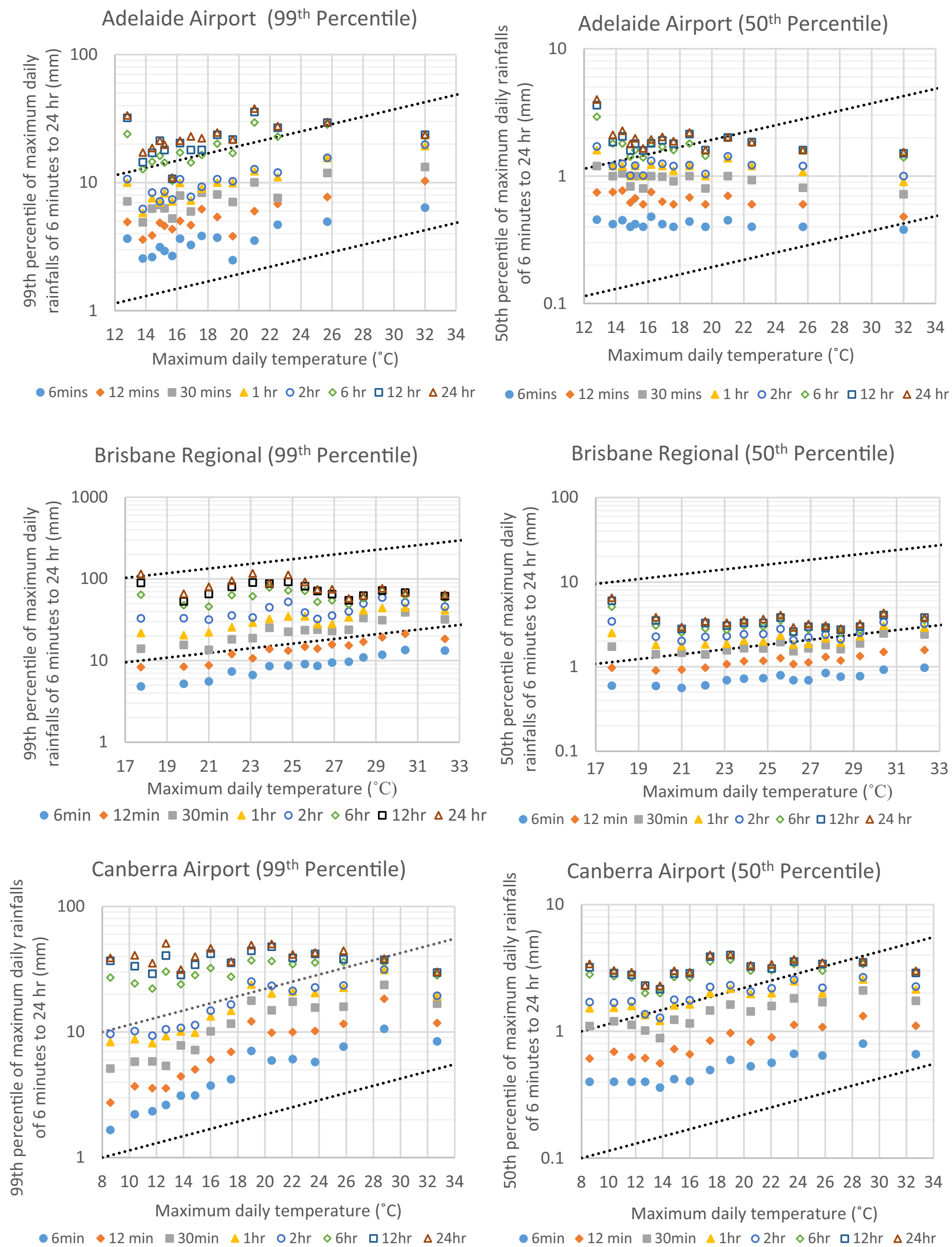


Figure 2. (a) The relationship between daily maximum temperature and the 99th percentile of the maximum daily rainfall durations (6 min to 24 h). Where the C-C scaling rate of 6.8%C^{-1} is represented by the dashed black lines. (b) The relationship between daily maximum temperature and the 50th percentile of the maximum daily rainfall durations (6 min to 24 h). Where the C-C scaling rate of 6.8%C^{-1} is represented by the dashed black lines.

takes a positive value for 6 min to 2 h duration for the 99th percentile. Further, the rate of scale varying for the events with short durations (6 min to approximately 2 h, in some stations it may vary from 6 min to 1 h or 6 h) is very low, but the rate of scale varying is very high in the long duration events (i.e. 2 h to 24 h range). The 6 min rainfall durations for the Brisbane (7.2%) and Canberra (6.9%) stations show the highest rainfall - temperature scale values. The Melbourne Airport station shows a positive scale for all the durations from 6 min to 24 h, while for all other stations the variation in scale becomes negative for the 2 h to 24 h duration range. However, the behaviour of the Darwin Airport station data are different to that from the other stations and in particular the data show a negative scale relationship for all the rainfall durations. The literature confirms that similar trends in scaling have been identified by other researchers for these parts of Australia (Wasko and Sharma, 2015). The data presented in Fig. 3(b) show that the 50th percentile rainfall - temperature scale values are lower than the 99th percentile values. The data also show a negative scale trend for all rainfall durations for the Adelaide, Darwin, Perth and Sydney stations, while positive trends are apparent for short duration rainfall events for the Brisbane, Canberra and Melbourne stations.

Furthermore, according to Fig. 3, sensitivity of temperature on more extreme rainfall is higher than average extreme rainfall events. It implies that rainfall –temperature scaling relationship is highly visible at more extreme rainfall events which saturate/release total water vapour amount in the atmosphere rather than average extreme rainfall events (Hardwick Jones et al., 2010).

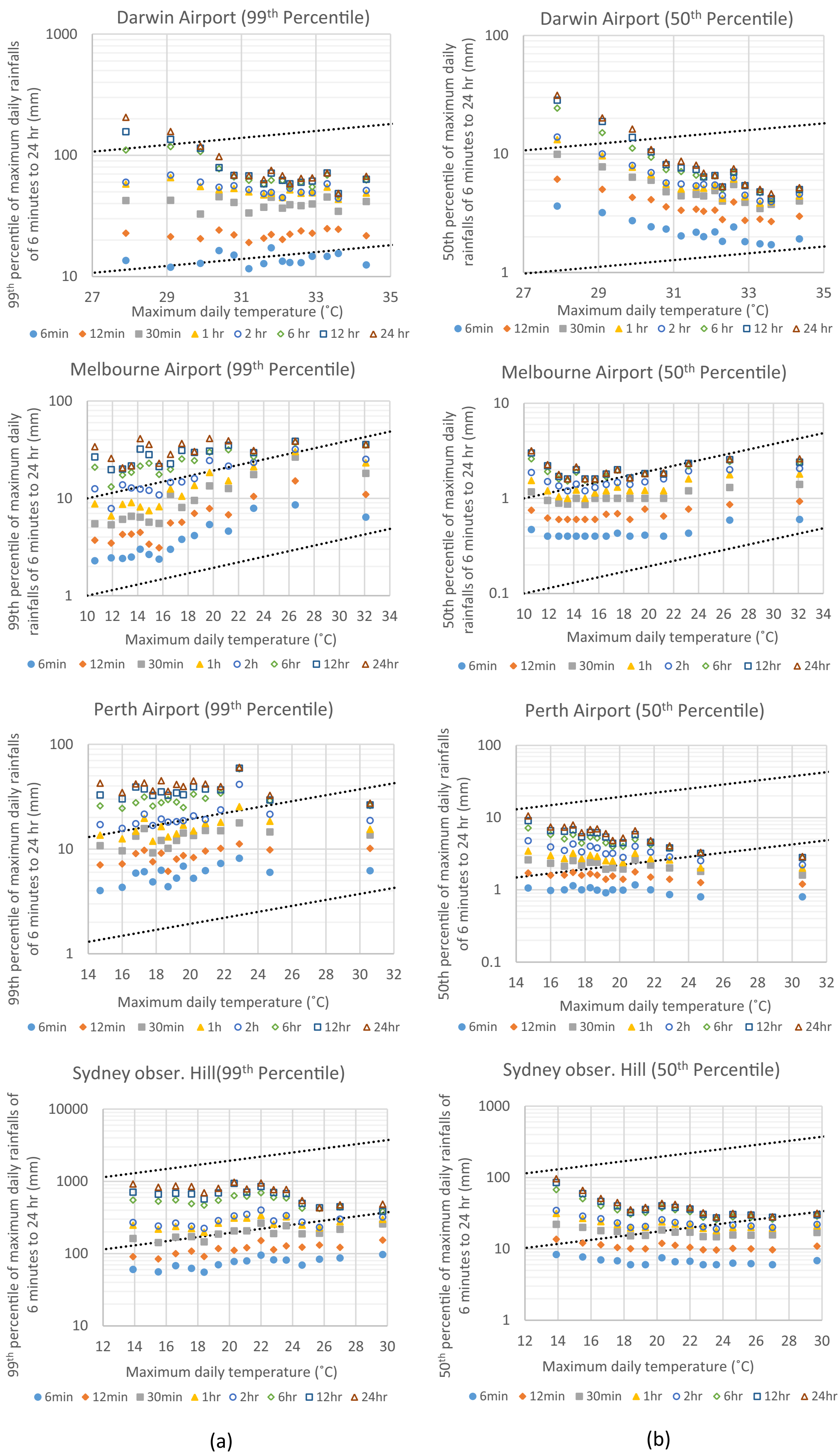


Fig. 2 (*continued*)

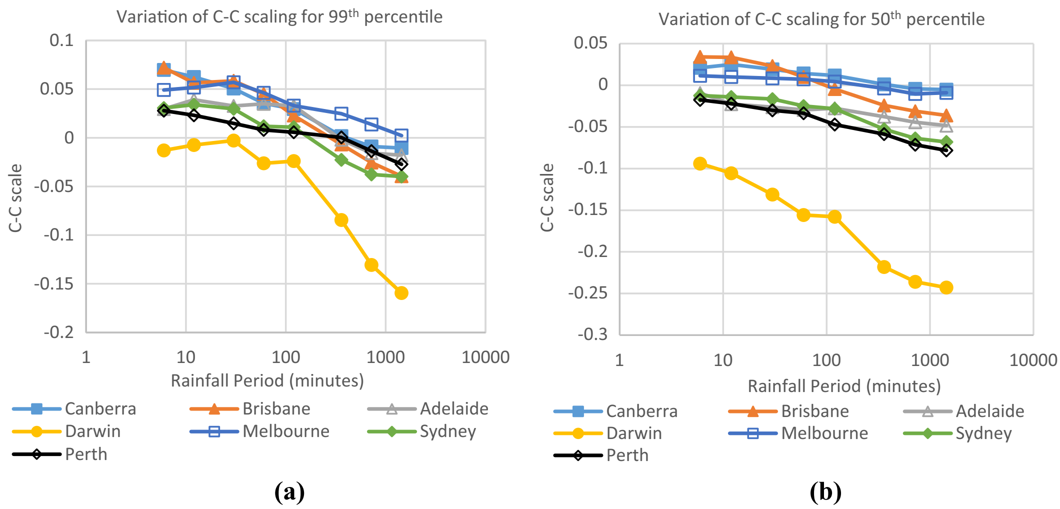


Figure 3. (a) Variations in C-C scaling with rainfall duration and location for the 99th percentile of daily maximum rainfall on wet days. (b) Variations in C-C scaling with rainfall duration and location for the 50th percentile of daily maximum rainfall on wet days.

4.2. Evaluating changes in rainfall - temperature scale trends over time

The trends in rainfall - temperature scale variation were evaluated for different windows of time. To allocate the adequate number of pairs into a single temperature bin, to minimise the sampling uncertainty, this evaluation was conducted for 10 year time periods. Figs. 4–6 describe the variation of scale for the 99th and 50th percentiles of 6 min, 1 h and 24 h rainfall durations respectively. The least square method is used to determine the scaling variability with the time period.

It can be clearly observed that scales vary significantly from one time slice to the next. As the uncertainty of estimated regression lines is very low, it implies that climate factors behind the extreme rain events are changing with the time. In general, all the stations show significant changes within few decades. As uncertainty of the regressions lines is very low, it clearly verifies that changes are not due to the uncertainty. From Fig. 4(a) it can be observed that there is an increasing trend in C-C scale for the 99th percentile for 6 min extreme rainfall events at all stations except Adelaide Airport. Further, Melbourne and Perth Airports show the highest increasing trends. These trends demonstrate that the influence of daily maximum temperature on more extreme rainfall durations (above the 99th percentile) is increasing for all stations except Adelaide. Therefore, there is a significantly high risk of the occurrence of extreme rainfall events in the future under the influence of increasing daily temperatures.

Anyway, Fig. 4(b) presents the scaling trend for the 50th percentile of the 6 min extreme rainfall event and clearly shows that all rain gauge stations, except Brisbane, display a decreasing trend in scale over time. Among these decreasing trends, the Darwin station shows a significantly high rate of decrease.

Therefore, the influence of maximum temperature on the 50th percentile of 6 min duration rainfall events is less significant than the 99th percentile. It implies that the impact of future tempera-

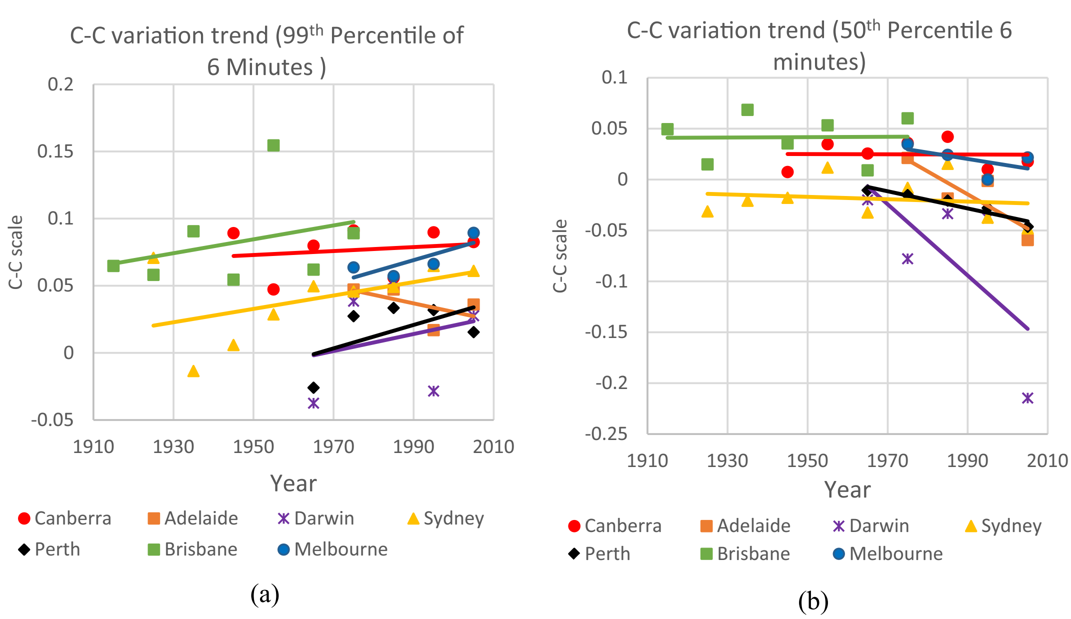
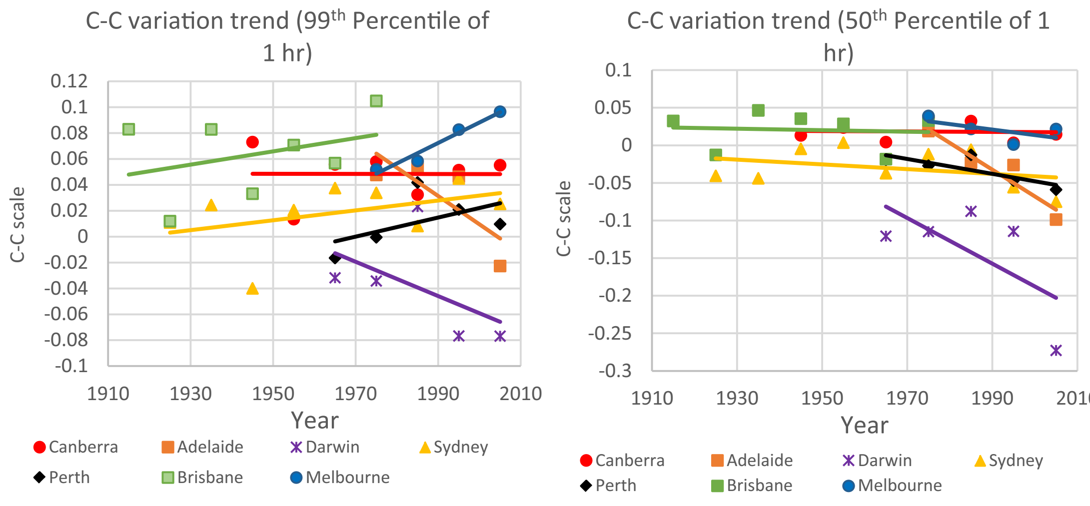
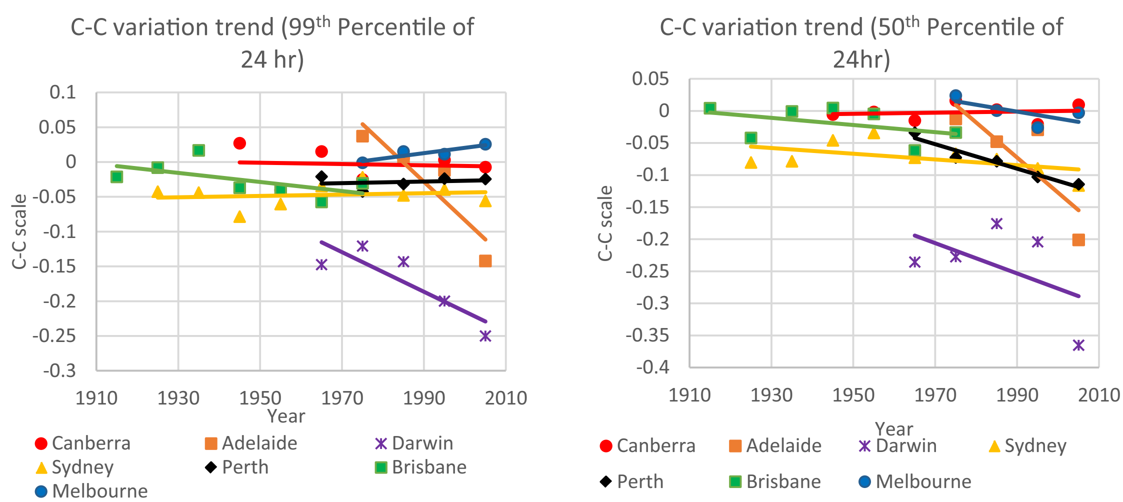


Figure 4. (a) C-C Scale variation for the 99th percentile of extreme sub-daily rainfall duration (6 min) over time. (b) C-C Scale variation for the 50th percentile of extreme sub-daily rainfall duration (6 min) over time.



(a) (b)

Figure 5. (a) C-C Scale variation for the 99th percentile of extreme sub-daily rainfall duration (1 h) over time. (b) C-C Scale variation for the 50th percentile of extreme sub-daily rainfall duration (1 h) over time.



(a) (b)

Figure 6. (a) C-C Scale variation for the 99th percentile of extreme 24 h rainfall duration over time. (b) C-C Scale variation for the 50th percentile of extreme 24 h rainfall duration over time.

ture change for average short period rainfalls is expected to be minimal, whereas impact on extreme rainfalls is significantly high.

Similar trend in scale variation of 1 h daily maximum rainfalls can be observed at all stations except one station in Fig. 5(a), the exception being the Darwin station, compared to Fig. 4(a). Fig. 5 (a) shows that the highest increasing trend in scaling occurs at the Melbourne station, while the Darwin and Adelaide stations display a decreasing trend in scaling. Fig. 5(b) describes the trend of scale variation for the 50th percentile of daily maximum 1 h rainfall duration and daily maximum temperature over time. According to Fig. 5(b), all station showing decreasing trends while the Adelaide and Darwin stations show the highest decreasing trend in scaling.

Fig. 6(a) describes the trend in rainfall - temperature scale for daily maximum temperature and the 99th percentile of daily rainfall. It is apparent that the scale changing trend of 99th percentile daily rainfall differs from the scale changing trend of 99th percentile of 6 min and 1 h rainfall events. According to Fig. 6(a), only the Melbourne, Perth, and Sydney stations show a slight increasing trend in the scale and all other stations show a decreasing trend in the scale. Fig. 6(b) describes the scaling trend of the 50th percentile of daily rainfall and it shows a decreasing trend for all stations except Canberra. These trends in extreme daily rainfall events suggest that increasing temperatures will have minimal influence on extreme daily rainfall, in contrast to 6 min extreme rainfall events. Therefore, it is clear that rainfall – temperature scale variation highly depends on location, rain duration and the extremeness of the rainfall.

To further confirm the accuracy of the described graphical results of rainfall – temperature scale variation trend over time, 95% Confidence Interval (CI) of the slope of proposed trend lines are compared with the estimated variability. To illustrate this, a comparison is presented in Table 2 for the 99th percentile of 6 min, 1 h and 24 h rainfall durations. The uncertainty estimates of trend lines are smaller than the estimated variabilities thus implying that the computed scale slope changes are significant.

Table 2
Comparison of Uncertainty and variability of trend lines.

Duration	Station	Scaling slope and 95% confidence interval	Variability range of scaling slope	Station	Scaling slope and 95% confidence interval	Variability range of scaling slope
6 min	Adelaide	−0.0006 ± 0.00046	0.03026	Melbourne	0.0009 ± 0.0007	0.03223
1 h		−0.0022 ± 0.0010	0.07660		0.0016 ± 0.0004	0.04460
24 h		−0.0055 ± 0.0035	0.17938		0.0008 ± 0.0005	0.02668
6 min	Brisbane	0.0005 ± 0.0003	0.09643	Perth	0.0009 ± 0.0005	0.05942
1 h		0.0005 ± 0.0004	0.09289		0.0007 ± 0.0001	0.05830
24 h		−0.0007 ± 0.0004	0.07407		0.0001 ± 0.00009	0.02134
6 min	Canberra	0.0008 ± 0.0007	0.04392	Sydney	0.0005 ± 0.0004	0.08430
1 h		−0.000004 ± 0.0008	0.05951		0.0004 ± 0.0002	0.08481
24 h		−0.00009 ± 0.00005	0.06755		0.00001 ± 0.00002	0.05656
6 min	Darwin	0.0006 ± 0.0004	0.09167			
1 h		−0.0013 ± 0.0002	0.10004			
24 h		−0.0028 ± 0.0019	0.12924			

Further, as estimated 95% CIs do not contain zero value, it justifies the statistical significance of proposed trends (except 24 h at Sydney and 1 h at Canberra). Also, the investigation of the uncertainty associated with 50th percentile of rainfall- temperature and seasonal rainfall– temperature scale variation trend lines (see Section 4.3) confirms that the scale slope changes in times are significant.

4.3. The impact of seasonal variation on rainfall-temperature scaling trends

Understanding the average temporal changes of seasonal variation in rainfall - temperature scaling trends is important as it enables the projection of seasonal influence on rainfall extremes in the future. For this analysis the summer and autumn months (Dec-May) were placed in one group and the winter and spring months (June-November) were placed in another. A trend analysis was then conducted to identify the changes in rainfall - temperature scale trend from extreme sub-daily rainfall events to daily maximum temperature. Fig. 7 describes the trend in the scale variation of the 99th percentile of extreme rainfall and daily maximum temperature seasonally. The data presented in Fig. 7 show an increasing trend in scale for the Melbourne, Perth and Sydney stations for summer and autumn rainfalls for all durations (6 min; 1 h; and 24 h). In contrast, the winter and spring rainfall events for Melbourne and Perth show increasing trend while Adelaide and Darwin show a decreasing trend. Fig. 8 presents the seasonal trend variation of the 50th percentile of extreme rainfall events

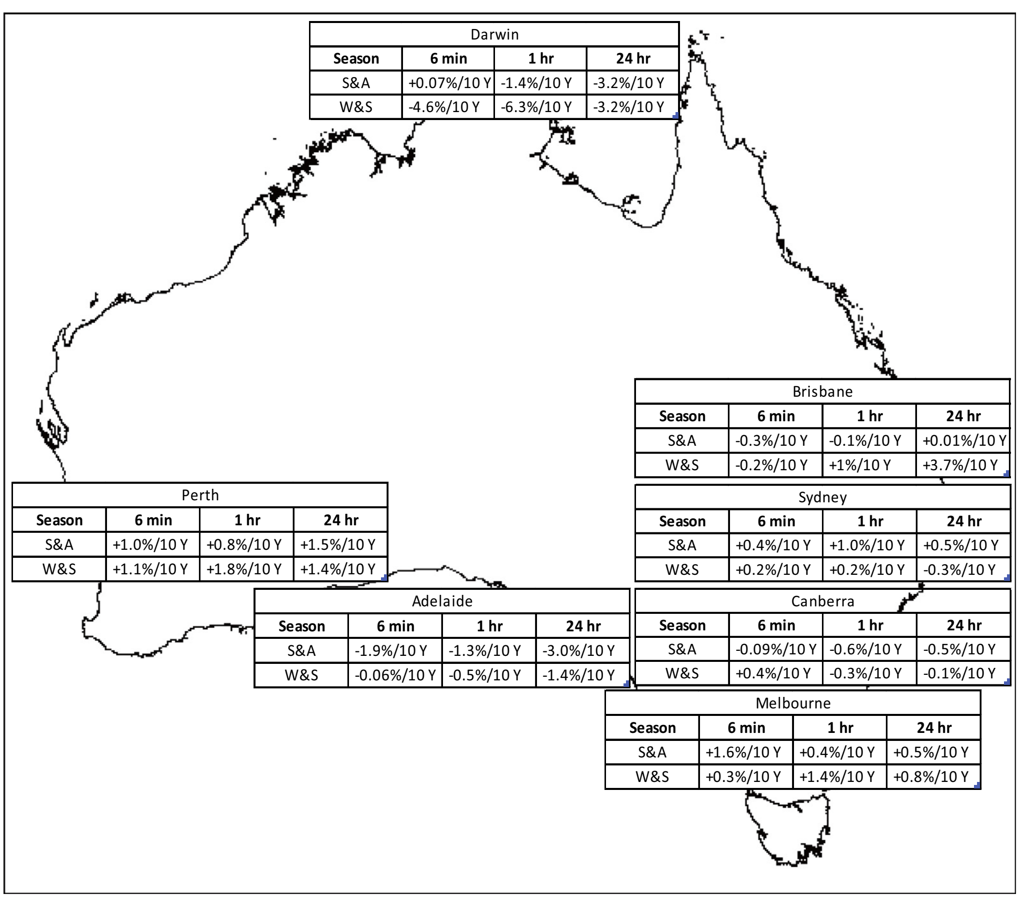


Figure 7. Seasonal variations in C-C scaling trends for the 99th percentile of 6 min, 1 h and 24 h rainfall durations with daily maximum temperature.

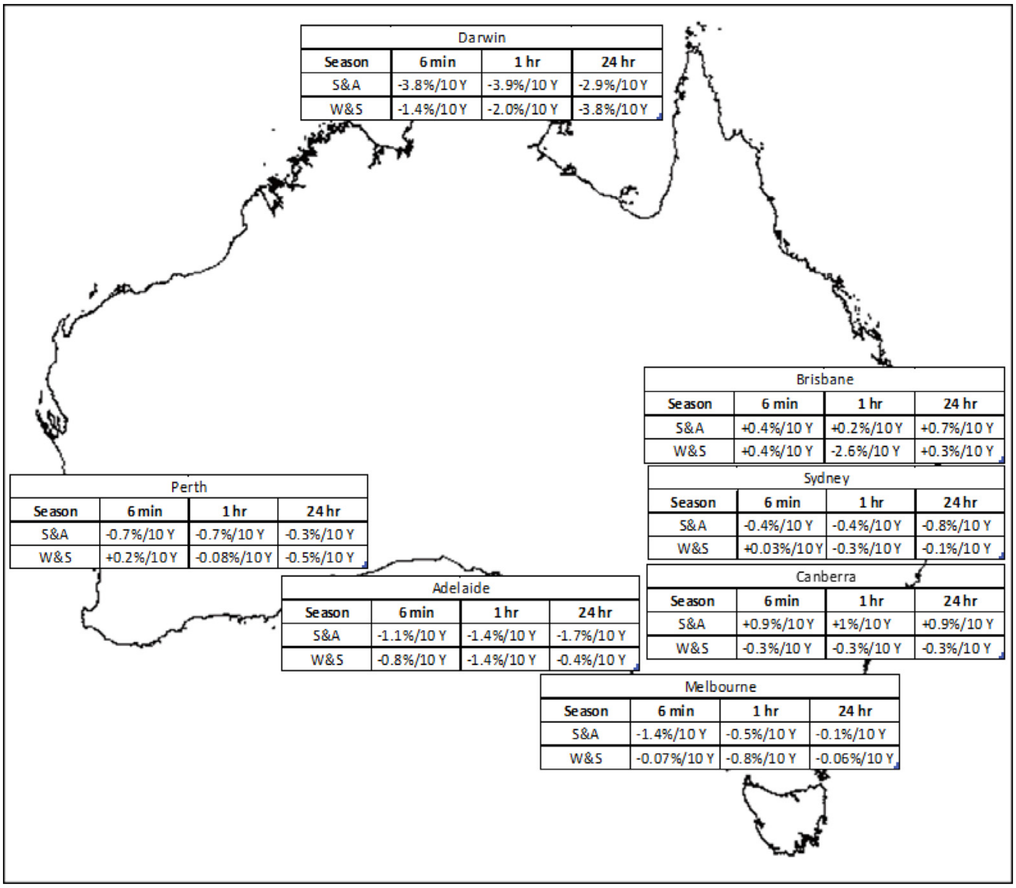


Figure 8. Seasonal variations in C-C scaling trends for the 50th percentile of 6 min, 1 h and 24 h rainfall durations with daily maximum temperature.

and daily maximum temperature. Based on the data presented in Fig. 8, the Adelaide, Darwin and Melbourne stations show a decreasing trend for both seasonal categories. While the Brisbane and Canberra stations show an increasing trend for the summer and autumn seasons. Furthermore, the Sydney station shows an increasing trend only for the winter and spring season for the 6 min duration rainfall events.

By comparing changes in rainfall - temperature scale trend for the seasonal 99th and 50th percentiles, it can be seen that the same trends are evident for the Adelaide and Darwin stations (with the exception of the 6 min duration events for the summer/autumn rainfall for Darwin). The Melbourne and Perth stations show completely opposite trends in 99th and 50th percentile (with the exception of the 6 min duration events for the winter/spring rainfall for Perth). However, magnitude of the scale changing trend is highly variable due to the changes of seasonal storm types, circulation patterns in different stations. Seasonal scale trends for the Brisbane, Canberra and Sydney stations are varied and it is difficult to identify any patterns.

These observations indicate the important role of different climatic factors play in the occurrence of seasonal rainfalls and rainfall – temperature scale, which is not surprising given that the processes driving rainfall are complex. The intensity of extreme rainfall event depends on the combined impact of many number of variables. However, atmospheric temperature is one of the dominant variables driving the occurrence of intense rainfall events. Specially, slow moving thunderstorms, strong lows and tropical cyclone have significant impacts on local extreme rainfall events which make variations in rainfall -temperature scale. Also, large scale motion of the atmosphere (Emori and Brown, 2005) has a significant impact on extreme rainfall events and changes in moist-adiabatic lapse rates (O'Gorman and Schneider, 2009) is one of the reasons why variations in the scale occur. Furthermore, local Occurrence of precipitation extremes does not scale with water vapour content due to changes in moist-adiabatic lapse rates and temperature anomalies. Changing cloud characteristics during rainfall events (KE, 2011; Trenberth et al., 2003) also have a significant impact on rainfall depth. Also, high intense convective rainfall events show significantly high rainfall - temperature scaling relationship rather than stratiform rainfall events (Molnar et al., 2015). Therefore, consequent changing patterns in rainfall - temperature scale could be explained by the combined impact of all these variables.

5. Conclusion

The empirical relationship between extreme intensities on daily maximum temperature was investigated in this study using data from seven weather stations located throughout Australia (Adelaide, Brisbane, Canberra, Darwin, Melbourne, Perth and Sydney). The scaling relationship for daily maximum temperature and the 99th and 50th percentile of 6 min, 12 min, 30 min, 1 h, 2 h, 6 h, 12 h and 24 h daily maximum rainfall for wet days (rainfall >0.3 mm) was analysed. To minimise the bias associated with C-C scale analysis, a technique placing an equal number of pairs in designated temperature bins was used to analyse the relationship. The initial analysis was conducted by considering the total data period as a single window.

The results of this analysis were consistent with results reported in the literature, with rainfall –temperature scaling relationships found for all stations and evidence that the scale varies

with location, rain duration and temperature. Darwin station showed a negative scale relationship for both the 50th and 99th percentiles for all rainfall durations. It is located in Northern territory, which has tropical climate throughout the year. Similar negative scale at weather stations under tropical climate (in northern territory) are observed by (Hardwick Jones et al., 2010). The other six stations showed similar patterns in scale relationship with the highest scale values resulting for 6 min rainfall durations and the lowest for 24 h rainfall durations for both percentiles. These results imply that short duration rainfall events are more dependent on daily maximum temperature than long duration rainfall events. However, scaling values vary with the percentile of the rainfall event, with the 99th percentile always producing a higher value than the 50th percentile. Therefore, we can conclude that the relationship between daily maximum temperature and more extreme rainfall events (not the daily maximum) is stronger than the relationship with average rainfall events. Further, scale is not constant over a range of temperatures, with deviation especially evident at the lower and upper ends of the temperature range. The results also show that the positive scaling range is independent from station to station. Similar behaviours are identified by other researchers in Australia and other part of the world (Berg et al., 2009; Hardwick Jones et al., 2010).

To identify the variation of this scale with time, data was then analysed using 10 year data windows. The 99th and 50th percentiles of 6 min, 1 h and 24 h rainfall events were studied. The Adelaide station showed a significantly high decreasing rate of the scale for all rainfall events for both percentiles. The Darwin station also showed a decreasing trend in scale for all events with the exception of the 99th percentile of 6 min rainfall events. In comparison, the other five stations showed an increasing trend in the scale for the 99th percentile of 6 min rainfall events. This increasing trend may be caused by frequent intensified convictive rainfall events as a result of climate change. Further, the results also show a decreasing trend in the scale, especially for the 50th percentile of long duration rainfall events.

Seasonal variations in the trend of the scale change were analysed by placing the summer and autumn seasons in one group and the winter and spring seasons in another group. The Perth, Melbourne and Sydney (except 24 h rainfall winter/spring) stations show increasing trend of scale for both groups while Adelaide and Darwin show decreasing trend for 99th percentile (except 6 min rainfall in summer/autumn). Furthermore, majority of scaling trend of 50th percentile are decreasing for both groups. The uncertainty estimates associated with the observed changes of scaling slopes, suggest that latter are significant.

Finally, these results clearly show that the rainfall - temperature scaling relationship is limited to certain temperature range, and this relationship depends on the percentile of rainfall, the rainfall duration, analysis period and the season. Both increasing and decreasing scaling trends were observed by periodic analysis. According to these results, it can be expected more extreme-short duration rainfalls in some regions in the future.

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